Applied Vehicle Technology Panel (AVT), Life Management Techniques for Aging Air Vehicles, Manchester, UK from 8-11 October 2001.

Widespread Fatigue Damage Assessment Approach

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Abstract

A methodology to assess the development of widespread fatigue damage (WFD) and its effect on the residual strength of aircraft structure has been developed. The three major components of the methodology are crack initiation, crack growth and linkup, and residual strength. The crack initiation methodology uses experimentally generated equivalent initial flaw size (EIFS) data and an analytical closure model to determine initial flaw sizes and distribution for multiple-site cracking. The crack-tip opening angle (CTOA) and the T* integral, and plastic zone touch (PZT) criteria were used to predict crack growth and linkup. Elastic-plastic finite element analyses were used with the CTOA or T* integral to determine the residual strength in the presence of multiple-site damage (MSD). The methodologies were verified through a comprehensive test program.

1. Introduction

In response to public concerns after the Aloha Accident, Congress passed legislation known as the Aviation Safety Research Act of 1988. The Act directs the FAA to develop technologies and conduct data analyses for predicting the effects of aircraft design, maintenance, testing, wear, and fatigue on the life of aircraft and on air safety and to develop methods of analyzing and improving aircraft maintenance technology and practices, including nondestructive inspection (NDI) of aircraft structures. The Act also includes a requirement to develop a better understanding of the relationship between human factors and aviation safety and to identify innovative and effective corrective measures for human errors that could adversely affect air safety.

As a result of the Aviation Safety Research Act and concerns relating to the increasing age of the air carrier fleet, the Federal Aviation Administration (FAA) developed the National Aging Aircraft Research Program (NAARP) to ensure the structural integrity of high-time, high-cycle aircraft.

Within the NAARP, the FAA is actively pursuing research to address the problems associated with ensuring the continued structural integrity of the aging commercial transport fleet. The NAARP structural integrity research and development program area includes three major elements: methodologies to assess widespread fatigue damage, airframe repair assessment, and supplemental structural inspections for commuter aircraft. This paper discusses the first element, the assessment of widespread fatigue damage.

2. Widespread Fatigue Damage

Widespread fatigue damage (WFD) in a structure is characterized by the simultaneous presence of cracks at multiple structural components where the cracks are of sufficient size and density that the structure will no longer meet its damage tolerance requirement. The two sources of WFD are multiple-site damage (MSD), characterized by the simultaneous presence of fatigue cracks in the same structural element; and multiple-element damage (MED), characterized by the simultaneous presence of fatigue cracks in similar adjacent structural elements. An industry committee on WFD identified 16 generic types of structure susceptible to WFD. A few examples are shown in Figure 1.

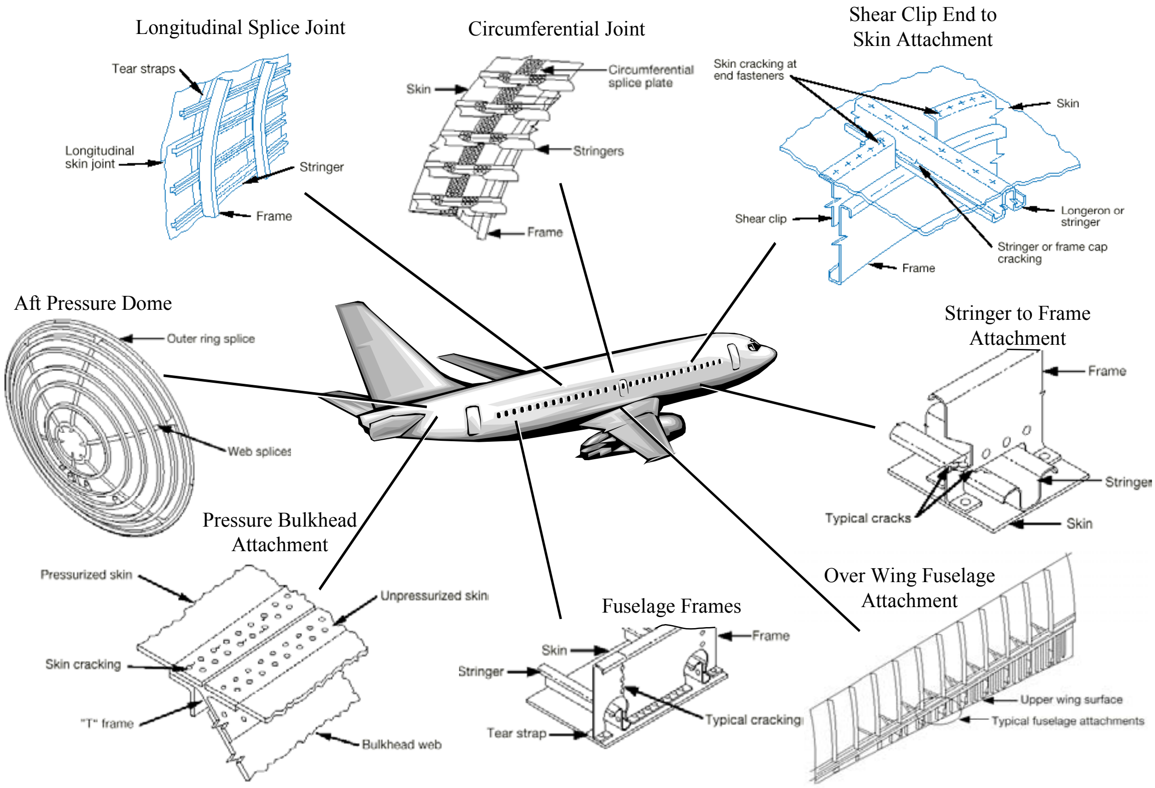

Figure 1. Susceptible widespread fatigue damage locations

WFD is a complex phenomena that is extremely difficult to analyze with standard methods developed from first principles of linear elastic fracture mechanics (LEFM). With limits on the applications of LEFM, more advanced methods have been explored and developed over the past decade with the support and sponsorship of the FAA and the National Aeronautics and Space Administration (NASA). This includes analytical tools to determine parameters governing the onset and growth of cracks and elastic-plastic fracture criterion for residual strength determinations. The tools include the finite element alternating method (FEAM) [1-3] a computationally efficient yet rigorous approach to calculate two- and three-dimensional stress-intensity factor (SIF) solutions governing crack formation and growth, FASTRAN [4], a fatigue crack growth analysis program using a crack closure model, and STAGS [5,6], an advanced finite element program implemented with fracture mechanics and stable tearing analysis capabilities for generalized shell structures. The elastic-plastic failure criterion include the plastic zone touch (PZT), originally developed by Swift [7], crack-tip opening angle (CTOA), originally developed by Wells [8] and later implemented and used extensively by Newman et al. [6,9], and the T* integral, developed by Atluri et al. [10,11].

These tools and criterion are capable of analyzing portions of the multiple-site crack initiation, growth, linkup, and catastrophic fracture process, and they also provide a framework for WFD assessment. They can also be used for future aircraft designs to prevent the occurrence of multiple-site cracking within the design life goal. A critical aspect is experimental validation of the tools and criterion in developing a WFD assessment approach. The methodology developed must be verified and validated using experimental data to ensure successful transfer of useable and accurate technology to industry.

The goal of this research is to ensure that the residual strength of an aging aircraft is not degraded below limit levels due to the occurrence of WFD. To realize this goal, a WDF assessment methodology has been developed to conduct a thorough residual strength evaluation of aircraft structure containing MSD. Throughout the development of this methodology, experimental tests were conducted to validate various components of the methodology including crack initiation, crack growth, and residual strength. Table 1 shows the variety of tests that were conducted by various government and industry agencies worldwide, including NASA Langley Research Center, Air Force Research Laboratory (AFRL), the National Institute of Standards and Testing (NIST), and the Dutch Nationaal Lucht- En Ruimtevaartlaboratorium (NLR), and the General Administration of Civil Aviation of China (CAAC). More recently, a collaborative test program was completed involving Boeing Aircraft Company, AFRL, CAAC, and the FAA William J. Hughes Technical Center as listed in the last two columns in Table 1.

Table 1. Test matrix for WFD assessments

	Foster-Miller (1991-1994)	Author D. Little (1990-1991)	Boeing, Seattle (1995-1996)	NLR (1992-1995)	NIST (1994-1995)	NASA Langley (1991-1999)	AFRL (1991-1994)	Boeing/AFRL/CAAC (1996-2001)	FAA-TC (1999-2001)
Coupons: Fatigue						93		36	
Coupons: Fracture						124			
Flat Panels: Fatigue		102		23					
Flat Panels: Residual Strength	12			23		5	18	12	
Stiffened Flat Panels: Res. Str.					12	5	2	12	
Subscale Cylinders: Fracture						5			
Unstiffened Curved Panels: Frac.	10					1			
Stiffened Curved Panels: Fatigue	8		2			2			7
Stiffened Curved Panels: Res. Str	19		2			4			4
Aft Pressure Bulkhead: Res. Str.								1	

3. Approach

The approach established to conduct WFD assessments, as shown schematically in Figure 2, is a product of the advanced tools and criterion described previously for the methodology development and test data for experimental validation. In this study, the approach is used to address WFD on two fronts: (1) characterizing MSD by studying the initiation and growth of cracks in the evolution of multiple-site cracks, and (2) determining the effects of MSD on the residual strength.

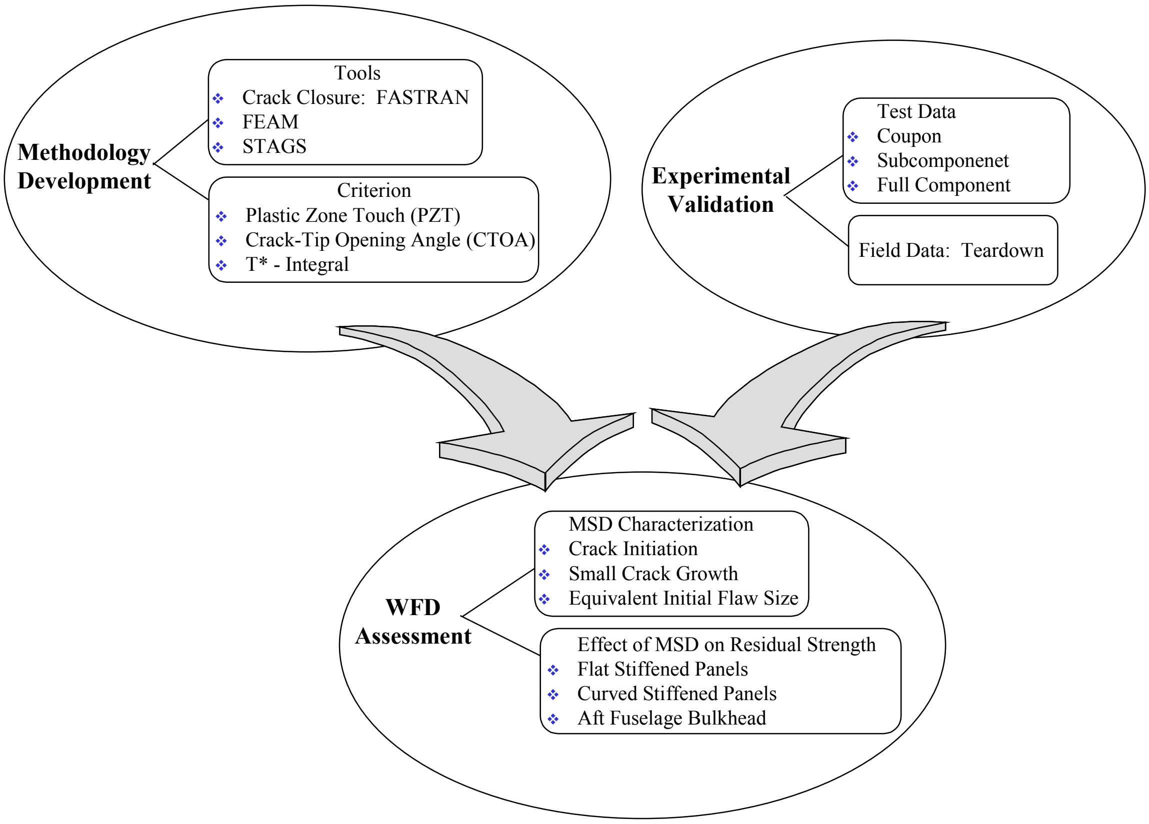

Figure 2. WFD methodology development, validation, and assessment

<u>Characterization of MSD Evolution</u>

One possible source of WFD is the occurrence of MSD along a structural component with similar details, for example, a lap splice with rows of riveted joints. Due to fatigue, small cracks of different sizes can emanate from each rivet hole. To accurately predict the initiation of these small cracks, the effects of rivet hole quality, interference fit, rivet load transfer, and rivet clamping forces need to be accounted for. However, these parameters are not easily determined individually. Therefore, an approximate approach, the equivalent initial flaw size (EIFS) approach was taken. In this approach, flat panels with structural splices were tested under fatigue loading. Crack growth was monitored using nondestructive inspection (NDI) techniques. The failed specimens were examined using a scanning electron microscope (SEM) to generate crack length versus cycles curves. The curves were then extrapolated to the "zero cycle" axis using the closure-based crack growth prediction code, FASTRAN, developed by NASA and that crack length was used as the EIFS.

Four common types of splice joints were considered as shown in Figure 3. A total of 16 flat-panel specimens were fabricated, four for each splice type. The splices represent three types of fuselage longitudinal splices and one type of fuselage circumferential splice.

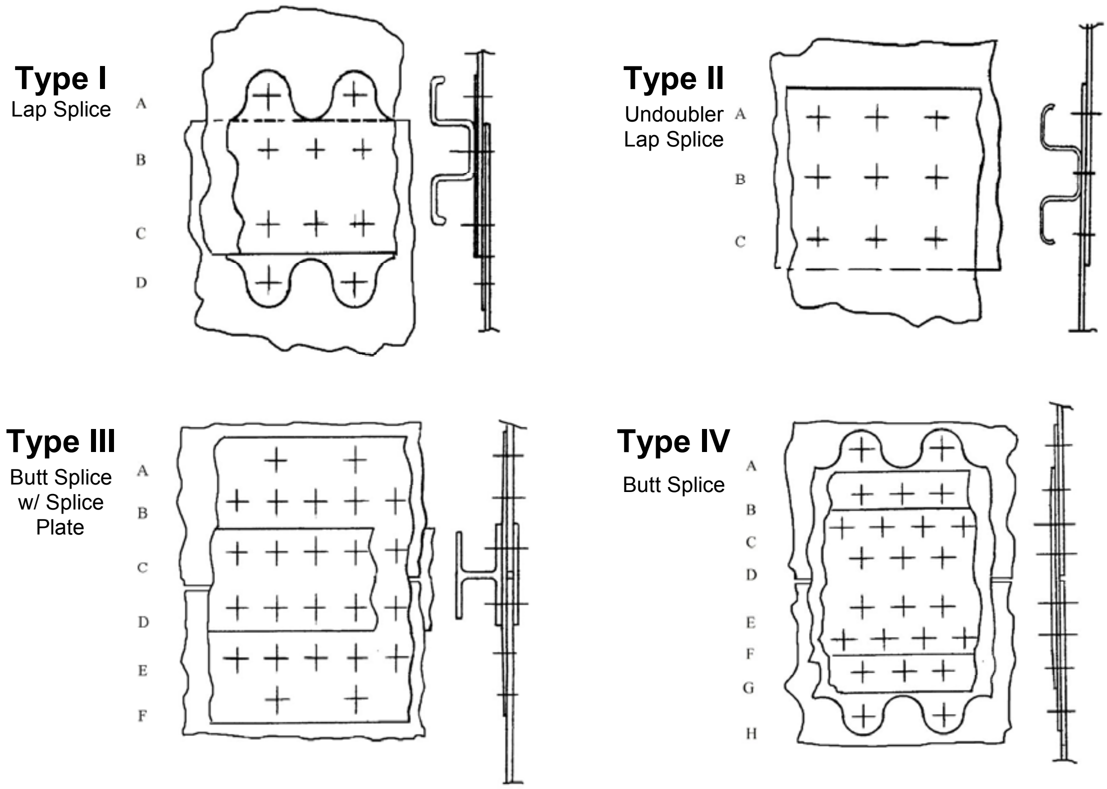

Figure 3. Three longitudinal splice type and one circumferential splice type

The three longitudinal splice types were (a) a lap joint with two finger doublers and a longeron; (b) a longitudinal lap joint without doublers but with a longeron; and (c) a longitudinal butt joint with a splice plate, a doubler, and a longeron. The circumferential splice type is a circumferential butt joint with a butt splice plate and a finger doubler. The skins were made of 2024-T3 aluminum alloy, the longerons were made of 7075-T6 aluminum alloy, and the doublers and splice plates were made of either 2024 or 7075 materials.

From the crack growth curves generated from the EIFS tests, as described above, the test and analysis were correlated using the NDI data and the SEM data. The closure-based crack growth prediction code, FASTRAN, and small crack growth rate data were used for the analyses. The parameters considered included the test specimen geometry, the test load history, magnitude of applied far-field stress, bending stress factor, bypass stress factor, neat-fit pin factor, and the effects of adjacent hole with cracks. A correlation factor as a function of crack length was then determined to obtain good agreement between analytical prediction and the experimental results for one specimen. This factor was subsequently used as the correlation factor for all other specimens. The EIFS distribution from the back tracking analysis using FASTRAN and an example of the correlation obtained between experiments and analysis using FASTRAN are shown in Figure 4.

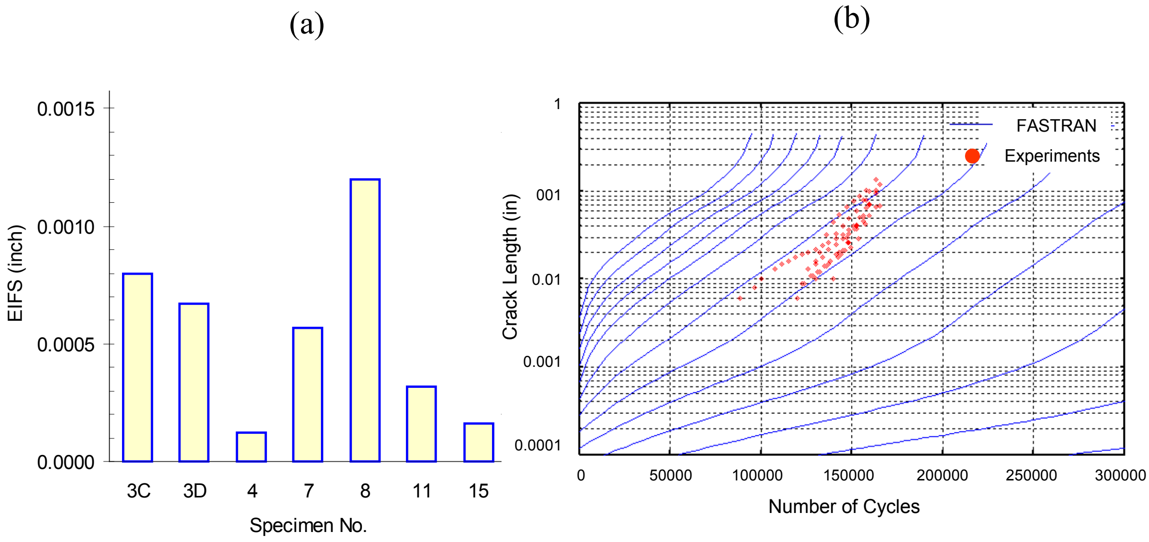

Figure 4. (a) EIFS distribution and (b) correlation between experiments and analysis using FASTRAN with different values of EIFS.

<u>Effects of MSD on Residual Strength</u>

A thorough residual strength assessment approach has been developed for aircraft structure containing MSD. The approach, based on nonlinear finite element analysis and the PZT, CTOA, and T* integral criterion, was applied and verified for three cases of problems outlined below.

MSD in Flat Panels

The effect of small MSD on residual strength was determined and the elastic-plastic criterion of T* integral, CTOA, and PZT fracture criteria were evaluated. These

Table 2. Residual strength prediction of flat panels.

Specimen Number	Joint Type	MSD Size (inch)	Criterion, Absolute Percent Difference Between Analysis and Experiments		
			PZT	T* integral	CTOA
1	1	0.00	-8	-	3
2		0.05	7	13	0
3		0.10	5	7	1
4	2	0.00	-13	-	-1
5		0.05	-10	-2	2
6		0.10	-1	-4	-6
7	3	0.00	-23	-	4
8		0.05	-3	-4	-2
9		0.10	0	-5	-5
10	4	0.00	-17	-	-5
11		0.05	-4	-3	-3
12		0.10	-4	-4	0
Average Percent Difference			7.9	5.2	2.7

criteria correlated well with the experimental results as shown in Table 2 with an average absolute percent difference of 2.7%, 5.2%, and 7.9% for the CTOA, T* integral and PZT criteria, respectively.

MSD in Curved Panels

A unique state-of-the-art facility to assess the structural integrity of aircraft fuselage structure was established at the Federal Aviation Administration (FAA) William J. Hughes Technical Center. The Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility is capable of testing full-scale fuselage panel specimens under conditions representative of those seen by an aircraft in actual operation. The test fixture features a novel adaptation of mechanical, fluid, and electronic components and is capable of applying pressurization, longitudinal, hoop, frame, and shear loads to a fuselage panel. A high-precision Remote Controlled Crack Monitoring (RCCM) system was developed to inspect and record crack initiation and progression over the entire fuselage panel test surface.

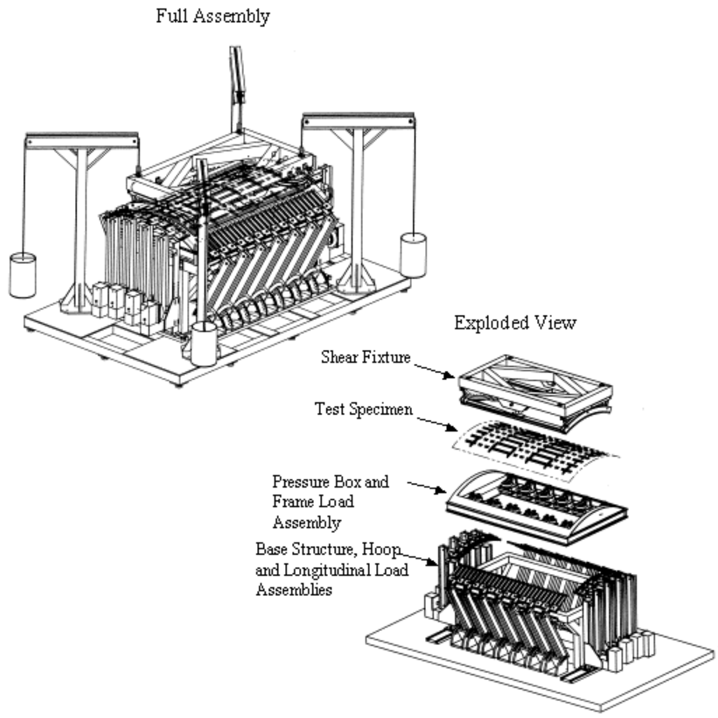

Figure 5. Full-Scale Aircraft Structural Test Evaluation and Research fixture

The effects of multiple cracks on the fatigue crack growth and residual strength of curved fuselage panels was studied using the FASTER facility. A total of four panels were tested, two panels with a longitudinal lap splice and two with a circumferential butt joint. For each joint configuration, one panel contained only a lead crack and the other contained a lead crack with multiple cracks located along the outer critical rivet row of the joints. Geometric nonlinear finite element analyses conducted using STAGS and the CTOA criteria were used to predict the residual strength. The strain distributions and fracture parameters governing crack formation and growth were determined. Comparisons with strain gage data verified the finite element models. Results include comparisons of strain distributions, fatigue crack growth characteristics, and the damage growth process during residual strength test for the two joint configurations. In general, the small multiple cracks did not have an effect on the overall global strain response. However, the small multiple cracks reduced the number of cycles to grow a fatigue crack to a predetermined length by 37% and 27% for the longitudinal lap joint and circumferential butt joint panels, respectively. In addition, the presence of multiple cracks reduced the residual strength of the panels with a longitudinal lap joint by approximately 20%. The measured and predicted residual strength were in good agreement as shown in Figure 6.

Panel	Residual Strength (psi) Measured	Residual Strength (psi) Predicted
CVP1	11.14	10.65
CVP2	9.16	9.58

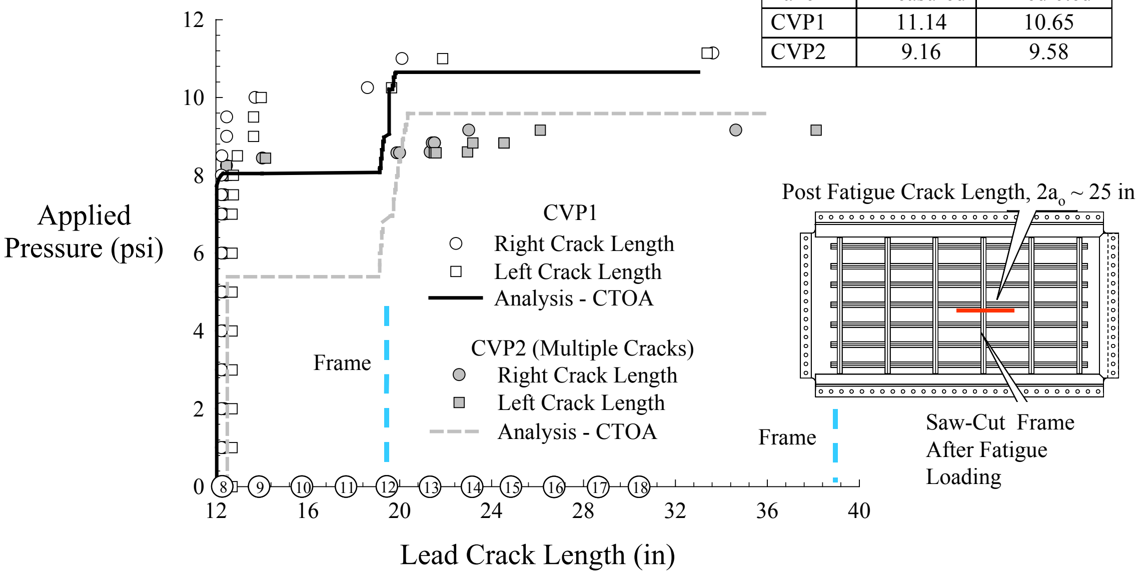

Figure 6. Measured and predicted residual strength

MSD in Aft Pressure Bulkhead

The purpose of this test was to verify the generality of the approach validated for the flat- and curved-panel cases by applying it to a different large-scale airframe structure, that is, to an aft pressure bulkhead. Geometric nonlinear finite element analyses using STAGS and the CTOA criteria predicted the residual strength. The measured and predicted residual strength were in good agreement as indicated in Figure 7.

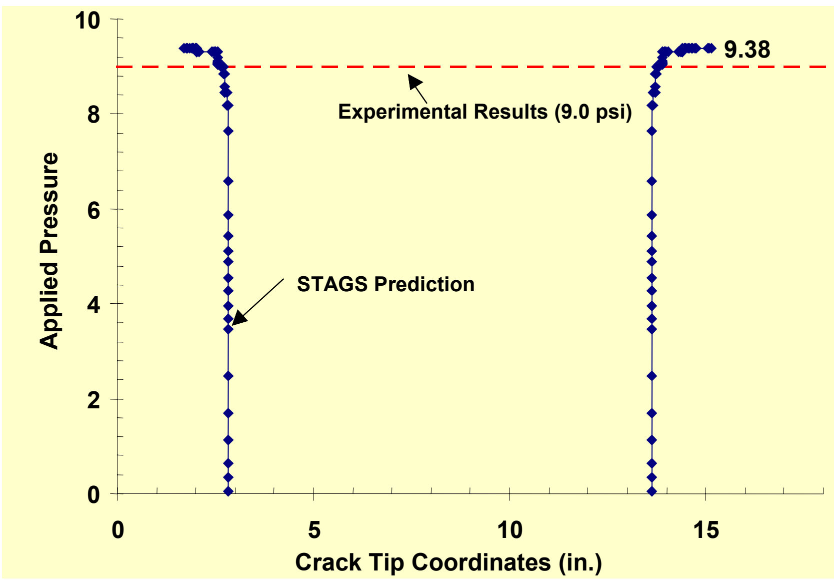

Figure 7. Measured and predicted residual strength

CONCLUDING REMARKS

An approach has been developed to assess the effect of widespread fatigue damage (WFD) on the residual strength of aircraft structure. The three major components of the approach are crack initiation, crack growth and linkup, and residual strength. The crack initiation methodology uses experimentally generated equivalent initial flaw size (EIFS) data and an analytical closure model to determine initial flaw sizes and distribution for multiple-site cracking. The crack tip opening angle (CTOA), T* integral, and plastic zone touch (PZT) criteria were used to determine crack growth and linkup and the residual strength in the presence of multiple-site damage (MSD). Good correlation was obtained between laboratory coupons and large-panel test data and the analytical predictive methodologies. The methodologies were verified for representative commercial aircraft panels under simulated flight conditions.

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